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Determination of the Fracture Toughness Parameters of Cement Composite Using Specimens with Rounded Notch

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The fracture mechanics parameters are used in different applications to formulae the classic criteria of failure as well as in computational models to analyze the concrete structures and other brittle materials. The parameters are determined using the specimens with notches. The study for assessing the influence of the notch curvature in specimen on fracture mechanics parameters, e.g. critical stress intensity factor, critical crack tip opening displacement and fracture energy, was performed on cement mortar as a typical quasi-brittle material. The U-shaped notches with a depth of 30 mm were formed during molding the specimens. The radius of notch curvature was changed in the range from 0.15 mm to 30.0 mm. The results obtained demonstrated that the notch curvature radius has a significant effect on the level of maximum stress and the parameters describing the cement composite resistance to cracking. Therefore, the experimental determination of the fracture characteristics requires a strict definition of the test conditions.

KEYWORDS: fine grained concrete, fracture mechanics parameters, U-shaped notch.

Introduction

The cracking process of the element of quasi-brittle material with heterogeneous microstructure (eg. cement based composites) is associated with the formation and propagation of the main crack called a critical defect. In the vicinity of defects such as fissure, air void, microcrack, etc. the local stress concentrations occur caused by external forces, which under certain conditions can cause rapid propagation of damage and total destruction of a structural member. The methods of fracture mechanics allow to describe the process of destruction of this type of material (Bažant 2002, Shah et al. 1995), as well as degradation which results from the impact of service life conditions (Kosior-Kazberuk 2012, Wardeh and Ghorbel 2015).

Notches in structural elements are places where stresses concentrate and, because of that, can trigger cracks leading to catastrophic failure or to a shortening of the assessed structural life. The phenomenon of cracking of construction and building materials is so common that there is a need to conduct the research to establish an easy-to-implement method of determining the values of parameters describing material's resistance to cracking.

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The critical stress intensity factor determined experimentally using samples with notch (Jenq and Shah 1991) is the fundamental material parameter of linear elastic fracture mechanics. In case of metals the procedure of determining this parameter is standardized and universally applied. The process of fracture starts up from the pre-existing sharp crack tip initiated by a fatigue loading. For cement composites and other brittle materials, fracture mechanics parameter identification requires the tests on the sample elements with pre-formed initial crack or notch. For brittle materials, such as concrete, ceramics or rocks, the process of obtainment the initial crack is difficult to control. During standard tests of quasi-brittle materials the elongate U-notches with a width from 1 to 10 mm are used, and the influence of rounded notch tip is skipped. Normally the notch is formed during casting of sample, or by cutting using diamond saw (Kosior-Kazberuk and Kazberuk 2010). The U-shaped notches obtained in this manner are 2-3 mm width and have similar notch tip rounding diameter. Consequently, all other dimensions of specimen must be relatively large, which raises costs of research. This approach is easy to implement, but includes a narrow spectrum of geometry notches (cracks), and does not explain in which range of the geometry of initial defects the process of crack propagation should be analyzed based on the criteria of strength of materials, and in which – on the basis of fracture mechanics (Berto et al. 2013, Berto and Barati 2011).

Most previous researches on the effects of U-notch on fracture mechanics parameters, focused on theoretical considerations rather than on test methods, were conducted using the materials such as polymethyl methacrylate (Berto et al. 2013), metal alloys (Berto and Barati 2011, Gomez et al. 2008), graphite (Torabi 2013). The results of the study indicate a significant influence of the radius of the notch tip on the value of the destructive force and the process of cracking. The tests conducted using concrete samples related mainly to the effect of the notch depth on fracture characteristics (Wardeh and Ghorbel 2015). Also, the influence of the notch radius on the fracture toughness measurements must be taken into account (Gomez and Elices 2006, Picard et al. 2006). In case of the notches with rounded tip, i.e., those for which the value of the tip radius in relation to the depth of notch is important, the singularity of stress disappears, and therefore, the criteria of fracture based on a linear elastic fracture mechanics can not be applied even in the case of brittle materials (Gomez et al. 2008).

The aim of the work was the assessment of the changes in fracture toughness of cement composite samples depending on the radius of the notch initiating cracking process. The experimental investigation was conducted using the procedure in which a sample in the form of beam with formed a single notch is loaded in three-point-bending test in accordance with Mode I conditions.

Materials and Methods

For experimental studies to evaluate the effect of rounding notch on the fracture mechanics parameters the mortar based on Portland cement (CEM I 42,5 HSR NA) with density 3050 kg/m^3 was used as typical quasi-brittle material easy to form. Fine quartz sand (0-2 mm) with density 2620 kg/m^3 was used as an aggregate. The limitation of the grain size was intended to eliminate the possible effect of coarse aggregate on the fracture characteristics. The water-cement ratio (w/c) mortar was 0.35. The required workability was obtained using a superplasticizer based on modified polycarboxylate (0.8% of cement mass).

The mechanical properties of mortar were determined. Three beams of size 100×100×400 mm were used for flexural strength test, three cubes (100×100×100 mm) were used for the compressive strength test. Three cylinders (h=300 mm, d=150 mm) were used for Young's modulus determination. The average compressive strength of mortar after 90 days of curing was 51.7 MPa, the average tensile strength was 4.01 MPa and tangent modulus of elasticity, determined from measurements of fracture mechanics parameters reached a value of 22.3 GPa.

The specimens of size 400×100×100 mm were prepared. All specimens were weakened by U-notches characterized by different values of notch tip radius and the same notch depth of 30 mm (the ratio a_0/d =0.30), that were formed during casting. Special disposable inserts for moulds were designed. The notch radius ρ was equal to 0.15; 0,35 mm; 0,65 mm; 1,35 mm; 3,15 mm; 8,0 mm; 15,0 mm; to 30.0 mm were used. For comparison the specimen series with conventional notch cut using a diamond saw (width of 3 mm) were tested. Each series of specimens was composed of four elements. After demoulding all specimens were stored in water at the temperature of 20±2°C for 90 days.

The effect of notch tip radius ρ in specimen on a critical value of the stress intensity factor and fracture parameters of cement composite was analyzed. The critical stress intensity factor K_{Ic}^{s} and the critical tip opening displacement $CTOD_c$ were determined according to the procedure proposed by RILEM TC 89-FMT (1990), developed on the basis of the two-parameters fracture model described by Shah et al. (1995). Both parameters are related to the critical stress σ_c initiating the crack propagation and the effective length of the critical crack a_c according to the following relationships:

$$K_{Ic}^{s} = \sigma_c \sqrt{\pi a_c}\, g_1\left(\frac{a_c}{b}\right), \quad (1)$$

$$\mathrm{CMOD}_c = \frac{4\sigma_c a_c}{E} g_2\left(\frac{a_c}{b}\right), \quad (2)$$

$$\mathrm{CTOD}_c = \mathrm{CMOD}_c\, g_3\left(\frac{a_c}{b}, \frac{a_0}{b}\right), \quad (3)$$

where:

where g_1, g_2, and g_3 are geometrical functions.

The beam elements with U-notch were loaded in three-point bending test corresponding to Mode I conditions. Dimensions and method of loading of a test specimen was showed in Fig. 1.

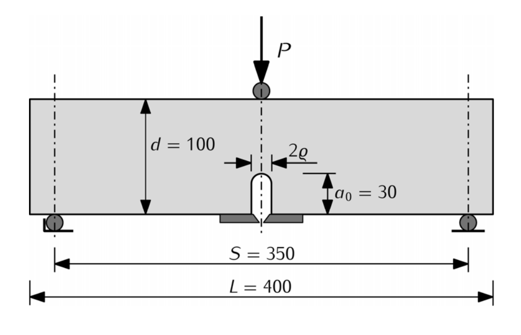

Fig. 1

Fracture testing configuration and geometry of specimen

During the test the loading force P as a function of the increase in the notch opening (notch mouth opening displacement △NMOD) was recorded. The universal testing machine (MTS 322) with closed-loop servo control was used to achieve a stable failure of specimens. The complete load-time curve was recorded to check the stability during the test. The test was performed with constant rate of deformation, so that the maximum load was reached within 30 – 60 seconds after start of the test. Fig. 2 shows the testing machine with beam specimen.

The basis for determining the value necessary for the calculation of the fracture parameters was a load P-△NMOD curve obtained as a result of cyclic loading and unloading of the beam with notch. The increase in the width of the notch opening was measured using a clip gauge with a base length of 5 mm. Before measuring the weight of the sample was determined and its dimensions were controlled.

The crack initiated in the bottom of the notch due to the influence of the tensile stresses developed until reaching a critical effective crack length a_c at which an unstable development of cracks occurred leading to the destruction of the test specimen.

The rate of loading was chosen so that the maximum value was reached within about 5 min. The rate was controlled by the constant rate of increment of crack mouth opening displacement. The

Fig. 2

Beam specimen with U-notch during testing

applied load was automatically reduced (unloading phase) when the load passed the maximum value and was about 95% of the peak load. When the applied load was reduced to ca. 100 N, reloading was applied. The cycles of loading and unloading were repeated four times, and then the specimen was loaded up to failure. At the same time, each successive cycle, after the initial, last no longer than 1 minute.

For assessment of the fracture mechanics parameters the initial loading compliance C_i and unloading compliance C_u were determined on the basis of the plot P- $\triangle$NMOD (RILEM 1990). The loading compliance (C_i) was calculated as the inverse of the slope from 10% of the peak load until 50% of the peak load. This was estimated to be the linear elastic range and ignored any initial seating load discontinuities in the curve. The unloading compliance (C_u) was the inverse of slope of the unloading curve. Determined, on the basis of C_i the initial elasticity modulus E was defined as the tangent modulus. The mid-span deflection δ of specimen with the applied load P were recorded continuously until the beam was completely separated into two halves.

The fracture energy (G_F) is defined as the area under the load-deflection curve per unit fractured surface area. The fracture energy of mortar tested in this experimental study, was evaluated using the equation given by RILEM TC 50-FMT (1985), in which energy was calculated from load-deflection curves obtained by performing a three-point bending test

$$G_F = \left[\int_0^{\delta_{\max}} P(\delta)d\delta + mg\delta_{\max}\right] / [(d-a_0)b], \tag{4}$$

where:
g = 9.81 m/s^2; d – beam depth;
b – beam width;
a_0 – notch depth;
δ_{max} – maximum deflection. In connection with the test, the weight of the beam m was determined and included into calculation of G_F.

The scatter of the calculated values of G_F results from the inevitable random length of the tail region of P-δ curve and also from the uncertainty in extrapolating the curve descent to zero. To reduce the impact of factors mentioned on the scatter of G_F the plot was excised when the load was approximately equal to 0.05 $P_{\max}$ (100÷200 N). On this basis, the value of δ_{max} was determined. The area of the cross section of specimen, to which the total energy value was referred, was determined based on the width of the test specimen b and the depth d excluding the notch (a_0 = 30 mm).

Results

Initial segments of P-DNMOD plots until reaching the maximum load for all radii of notch tip were showed in Fig. 3. On the basis of this part of the graph the initial compliance C_i was determined and the tangent elastic modulus was calculated. Linear section of the initial phase of P-DNMOD plot had an identical course independent of the radius of the notch in test specimen. Thus, the value of the elastic modulus, determined during the tests was independent of e. The analysis of P-DNMOD plots for different relative values of the radius of notch showed that the increase in e caused the increase in the length of linear section of the plots and the increase in maximum load. At the same time, the value of DNMOD, corresponding to the experimentally measured maximum load P_{max}, increased slightly.

The results obtained were given in **Table 1** as the dimensionless stress σ/σ_t describing the proportion of stresses at the tip of notch to flexural strength for different relative radius of the notch tip $\varepsilon = \rho/a_0$. With the increase in the radius of notch the level of destructive stress increased. For small values of $\boldsymbol{\varepsilon}$ the differences in stress values were the greatest; further the changes of stress proceeded smoothly. For large radii of curvature, i.e. $\varepsilon \geq 0{,}267$ ($\rho = 8{,}0$; 15,0 and 30,0), a value of destructive stress approached the flexural strength of mortar.

The fracture parameters K_{Ic} and $CTOD_c$ were determined on the basis of P-ΔNMOD curves obtained for concrete specimens with various radii of notch tip. The critical values of the stress intensity factor K_{Ic} as a function of the relative radius of the notch tip ε, plotted in logarithmic scale were shown in **Fig. 4**. The critical stress intensity factor increased with increasing values of ε. The black dot in **Fig. 4** indicated the value K_{Ic} determined using a test specimen with a conventional notch depth of 30.0 mm and a width of 3.0 mm cut using a diamond saw. For specimens with a formed U-notch the comparable values of critical stress intensity factor were obtained for relative radii of notch tip $\varepsilon \geq 0{,}267$. The changes in $CTOD_c$ (**Fig. 5**) were not as intensive as the changes in K_{Ic} and the character of the relationship was different. The uniform increase of $CTOD_c$ with the increase in radius of a notch tip was observed. The elastic modulus of mortar tested was constant during the test, thus the main parameter influenced the value of $CTOD_c$ (RILEM 1990) was P_{max}.

The significant parameter of non-linear fracture mechanics is the fracture energy G_F, defined as the amount of energy absorbed within the zone of destruction, per unit area (Bažant 2002). Fracture energy characterized the process of cracking and post-cracking strain

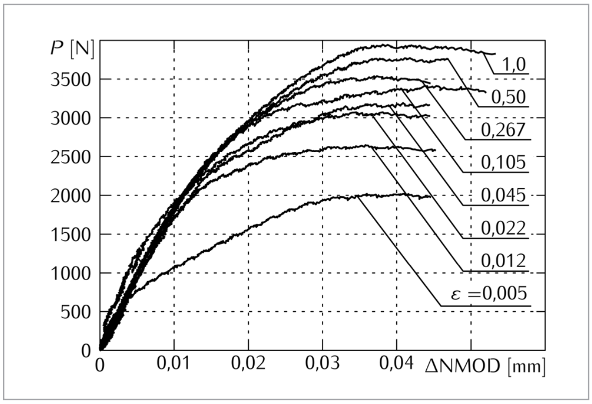

Fig. 3

Initial part of P-ΔNMOD curves vs. relative radius of notch curvature $\varepsilon = \rho/a_0$

$\varepsilon = \rho/a_0$	ρ/ρ_t
0,005	0,623
0,012	0,679
0,022	0,84
0,045	0,88
0,105	0,93
0,267	0,959
0,50	0,965
1,00	1,00

Table 1

Dimensionless stress ρ/ρ_t for different relative radius of notch curvature $\varepsilon = \rho/a_0$

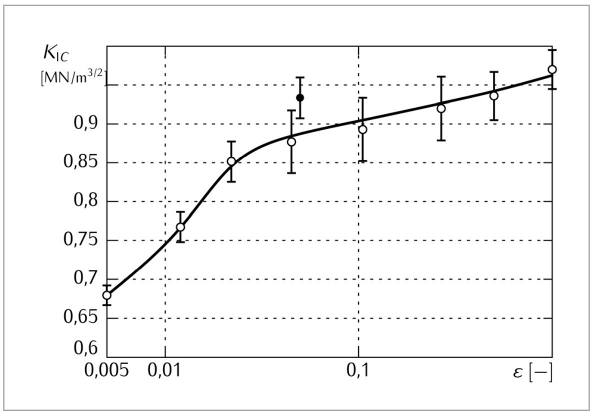

Fig. 4

Critical stress intensity factor K_{Ic} vs. relative radius of notch curvature $\varepsilon = \rho/a_0$, the black dot indicated K_{Ic} determined using the conventional specimen with saw cut notch

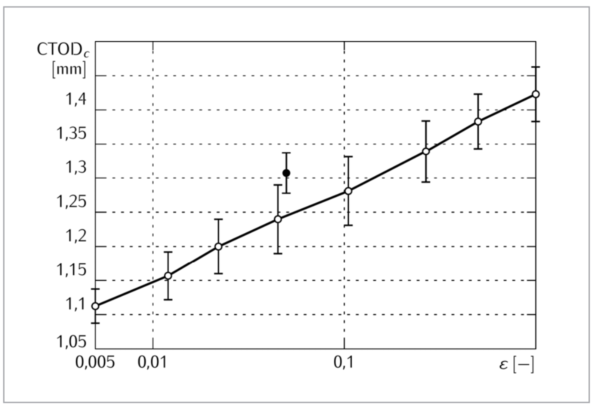

Fig. 5

Critical crack tip opening displacement $CTOD_c$ vs. relative radius of notch curvature $\varepsilon = \rho/a_0$, the black dot indicated $CTOD_c$ determined using the conventional specimen with saw cut notch

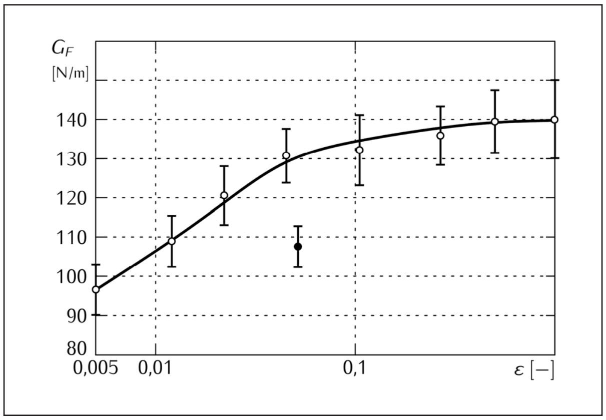

Fig. 6

Fracture energy G_F vs. relative radius of notch curvature $\varepsilon=\rho/a_0$, the black dot indicated G_F determined using the conventional specimen with saw cut notch

softening of material after reaching the maximum stress. The dependence of fracture energy G_F on the relative radius of the notch ε was shown in Fig. 6. The black dot indicated the amount of energy required to failure of the specimen with notch cut with a saw. The increase in G_F was the result of the increase in P_{max} and the increase in K_{Ic}. For $\varepsilon \geq$ 0,267 the changes in G_F were negligible. The amount of energy needed to fracture process initiation increased with the increase in the radius of the notch. As it was shown in Figs 4-6 the values of parameter determined in the same load conditions for specimens of the same geometry but with notch cut using a diamond saw were significantly different from the results obtained for samples with notch with a rounded tip. Experimental determination of fracture mechanics parameters of cement composites requires strictly defined test conditions. For blunted notches – i.e. when the notch radius is no longer negligible – the elastic stress singularity disappears and the fracture criterion of linear elastic fracture mechanics is no longer applicable, even for brittle material as cement mortar.

Conclusions

The results obtained confirmed the dependence of fracture mechanics parameters on the radius of the notch tip in the test specimen. With the increase in radius the extension of the linear segment of initial phase of the plot P- $\triangle$NMOD and the increase in the value of maximum load were observed. The values of the parameters analyzed: critical stress intensity factor, critical crack tip opening displacement and fracture energy also increased. The main reason for these changes was the increase in the energy required to initiate the process of cracking at the tip of rounded notch. Moreover, the way of notch forming, and as a result the shape of crack tip has a significant effect on fracture process initiation and fracture parameters. The results of the research are the basis for identifying the parameters of theoretical models of concrete elements cracking.

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